CONSTRAINTS ON THE FORMATION OF THE MOON FROM HIGH-PRECISION ND-ISOTOPIC MEASUREMENTS OF LUNAR BASALTS. K. Rankenburg[1], A. D. Brandon[1] and C. R. Neal[2]. [1]NASA Johnson Space Center, Mailcode KR, 2101 Nasa Road One, Houston, TX 77058, kai.rankenburg1@jsc.nasa.gov, [2]Dept. of Civil Eng. & Geological Science, University of Notre Dame, Notre Dame, IN 46556, neal.1@nd.edu.

Introduction: The most widely accepted theory for the formation of the Earth-Moon system proposes a giant impact model, where Earth collided in its later stages of accretion with a body of the approximate size of Mars [1, 2]. In this model, the Moon ultimately formed from hot debris generated during this giant impact. Short-lived radioisotopes such as ^{146}Sm ($t_{1/2}$ = 103 Ma) may be useful in determining the chronology of the events that formed the Earth-Moon system and for how these terrestrial bodies evolved following accretion. New high-precision samarium-neodymium data showed that chondritic meteorites are on average 20 ppm lower in ^{142}Nd/^{144}Nd than terrestrial samples [3]. These data suggest that if the bulk silicate Earth (BSE) has a Sm/Nd ratio within the range measured for chondrites, the higher-than-chondritic ^{142}Nd/^{144}Nd ratio of terrestrial materials requires that the silicate Earth experienced a global chemical differentiation during the lifetime of ^{146}Sm. If the Moon has super-chondritic ^{142}Nd/^{144}Nd identical to the Earth, as suggested by available data [4], then the giant impact must have occurred into an already differentiated Earth, predominantly sampling the Nd-depleted reservoir. In order to test this hypothesis, high-precision Nd-isotope ratios were obtained on a Thermo-Finnigan Triton TIMS for six lunar basalts that span the compositional range of lavas from the Moon: Samples 15555 and LAP 02205 represent low-Ti basalts; 70017 and 74275 are high-Ti basalts; 15386 and SAU 169 are KREEP basalts.

The lunar samples studied have crystallization ages of 2.96 to ~4 Ga and preserve a range of present-day ε^{142}Nd from -0.22 ± 0.05 (2σ) to +0.07 ± 0.05 when corrected for the effects of neutron irradiation. High-Ti samples 70017 and 74275 have ε^{142}Nd similar to the terrestrial value, suggesting that the lunar mantle experienced an early depletion or was formed from an initially depleted reservoir. However, low-Ti basalt 15555 has intermediate ε^{142}Nd and samples LAP 02205, SAU 169 and 15386 lie closer to the chondritic evolution.

The evolution of the lunar mantle was modeled for two end-member cases. In the first case (Fig. 1A), the Moon formed by a giant impact from material with average chondritic composition with present day ε^{143}Nd = 0 and ε^{142}Nd = -0.2 [3]. The ε^{143}Nd and ε^{142}Nd of the evolving lunar mantle is then calculated using a two-stage model.

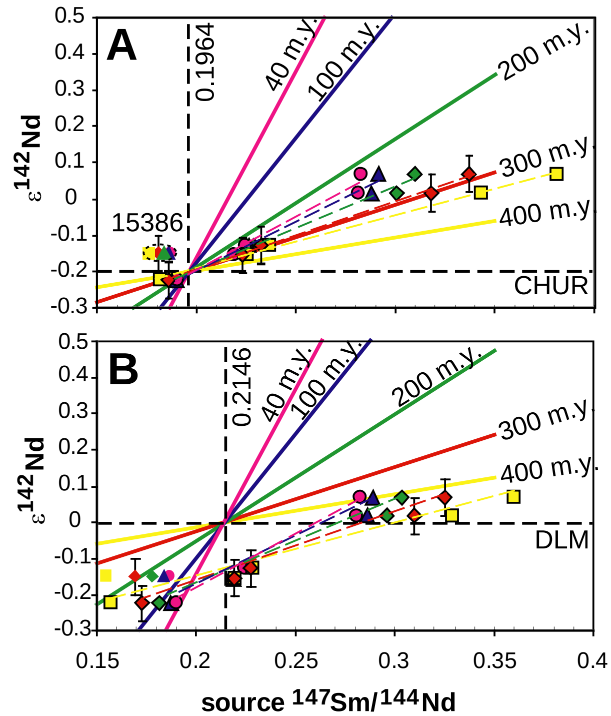

Fig. 1: Illustration of the interaction of ^{147}Sm/^{144}Nd, ε^{142}Nd and ε^{143}Nd. **A:** Source ^{147}Sm/^{144}Nd ratios for each sample (calculated at 40 (pink dots), 100 (blue triangles), 200 (green diamonds), 300 (red diamonds) and 400 m.y. after t_0 = 4567 Ma (yellow squares)) plotted versus measured present-day ε^{142}Nd along with regression lines for each age (broken lines in corresponding color). Also shown are ^{142}Nd-isochrons calculated for reservoirs formed from a chondritic LMO at 40, 100, 200, 300 and 400 m.y. (solid lines) using ^{147}Sm/^{144}Nd=0.1964, ^{146}Sm/^{144}Sm=0.0075 at t_0, and λ^{146}Sm= 6.74×10^{-9} yr^{-1}. A self-consistent model is obtained for t_1=287 m.y. **B:** Same samples as before, but calculated as three-stage model, in which the Moon was formed from a depleted source (DLM). The depletion age of 4537 Ma and ^{147}Sm/^{144}Nd=0.2146 correspond to the model of Boyet and Carlson [3], which forms the terrestrial MORB source with present-day ε^{142}Nd=0 and ε^{143}Nd=10.69.

In the second case (Fig. 1B), the Moon was formed from material that predominantly sampled the Nd-depleted reservoir of an already differentiated Earth and/or impactor. Here, ε^{143}Nd and ε^{142}Nd is calculated

using a three-stage model in which t_1 = 4537 Ma and $(^{147}Sm/^{144}Nd)_{t1}$ = 0.2146 [3], to yield a modern terrestrial depleted mantle reservoir with $\varepsilon^{143}Nd$ = +10.7 and $\varepsilon^{142}Nd$ = 0.

In the chondritic model (Fig. 1A), the $(^{147}Sm/^{144}Nd)_{t1}$ ratio was calculated for each basalt source using the $\varepsilon^{143}Nd_i$ and the crystallization ages of the basalts, and setting t_1 to 40, 100, 200, 300, and 400 m.y. after formation of the solar system at t_0 = 4567 Ma. Plotting these values versus the measured present-day $\varepsilon^{142}Nd$ for each time series t_1 forms straight lines, each passing through present-day CHUR. Generic isochrons form an independent set of lines passing through CHUR in Fig. 1A. Self-consistent values of $(^{147}Sm/^{144}Nd)_{t1}$ and t_1 are calculated for each sample by simultaneously solving the equations for the evolution of ^{142}Nd and ^{143}Nd. Except for sample 15386 which has no analytical solution, the calculated Sm/Nd closure age for the source region of all basalt samples is 287 ± 29 m.y. (2σ) after solar system formation (Fig. 2). Sample 15386 suffered the largest correction from neutron irradiation and likely is overcorrected. Regressing measured present-day $\varepsilon^{142}Nd$ versus best-fit $(^{147}Sm/^{144}Nd)_{t1}$ gives an intercept at the chondritic $\varepsilon^{142}Nd$ of = -0.204 ± 0.035 (MSWD=0.26), consistent with contemporaneous formation of the source regions represented in this study from a LMO with a present day $\varepsilon^{142}Nd$ = -0.204.

In the three stage model (Fig. 1B), where the Moon formed from depleted terrestrial upper mantle, self-consistent values of $^{147}Sm/^{144}Nd$, $\varepsilon^{142}Nd$ and $\varepsilon^{143}Nd$ could only be found for the two KREEP samples 15386 and SAU 169. The regressed lines also cannot be interpreted as simple mixing lines between KREEP (with low $^{147}Sm/^{144}Nd$) and depleted mantle (with high $^{147}Sm/^{144}Nd$) because formation of the KREEP source must equal or postdate formation of the depleted source, i.e. no line can be drawn connecting the KREEP reservoir, LAP 02205 and a depleted reservoir that is younger than KREEP. Assuming that the regression lines are isochrons and not mixing lines, then the age derived from the chondritic model should date the last global lunar mantle equilibration and cooling below the temperature of Sm-Nd isotope closure. However, the 287 m.y. datum derived here is in apparent contradiction with recent Hf-W isotope data of lunar metals, which seem to rule out a global lunar equilibration older than ~50 m.y. [5]. Nonetheless, the new high precision Nd isotope data clearly demonstrates that the bulk lunar magma ocean had a chondritic Nd isotope composition and was not formed from a depleted portion of the Earth's or impactor's mantle.

A suitable precursor material to build the Earth-Moon system directly with $\varepsilon^{142}Nd$ = 0 is missing in the meteorite collection. This implies that the Earth also started out with a chondritic composition similar to the Moon. Hence, in order to balance the Nd budget of the Earth where most samples today have $\varepsilon^{142}Nd \geq 0$ [6, 7], and obtain a chondritic composition for the Earth, an isolated enriched mantle reservoir must reside somewhere in the Earth at present. The conclusion that the Moon has $\varepsilon^{142}Nd$ close to the chondritic value does not constrain the relative timing of giant impact and early silicate fractionation on Earth. Assuming that approximately 80% of the Moon-forming material is derived from a chondritic impactor [2] and 20% from a hypothetical depleted Earth reservoir with present-day $\varepsilon^{142}Nd$ = 0, the measured lunar $\varepsilon^{142}Nd$ of -0.20 could be achieved if chondrites have an average $\varepsilon^{142}Nd$ of -0.25, which is well within the error limits given by Boyet and Carlson [3].

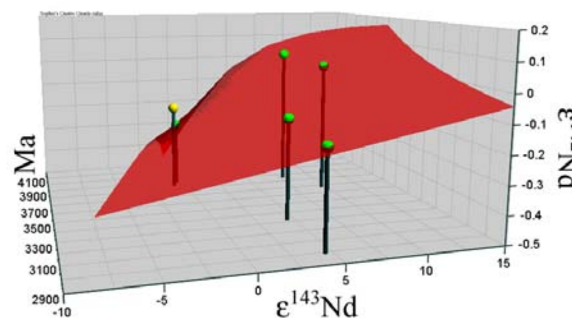

Fig. 2: Plane of Nd isotope compositions for LMO crystallization at 4280 Ma through time. Sample $\varepsilon^{142}Nd$ and $\varepsilon^{143}Nd$ at the time of their crystallization are represented by colored balls; the ball diameter corresponds to the approximate analytical error. All source regions except 15386 (yellow) are consistent with a uniform chondritic source which was variably fractionated at 4280 Ma.

References:

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